## 6.5 SEMICONDUCTORS (P AND N TYPE)

A pure semiconductor in which no impurity is added is called intrinsic conductor. The conductivity of a pure semiconductor depends upon the number of electrons excited from valence band to conduction band. Semiconductors can be in the form of elements on their compounds. Examples of elemental semiconductors are Germanium (*Ge*) and Silicon (*Si*) whereas inorganic compounds such as *CdS, GaAs, GaP, CdSe* and *InP* are some examples of compound semiconductors. The total current ($I$) in a semiconductor is the sum of current flowing due to electrons ($I_e$) and the current flowing due to holes ($I_h$) *i.e.* $I = I_e + I_h$.

**Point to Remember**

**All semiconductors have crystalline structure.**

## Limitations of Intrinsic Semiconductor

(i) In an intrinsic semiconductor, the number of intrinsic charge carriers at room temperature is very small ($\approx 10^{16}$ per $m^3$).

**Point to Remember**

**Ge is obtained from ash of coals and from flue dust of zinc smelters.**

(ii) The breakage of covalent bonds due to thermal motion is the only cause of production of intrinsic charge carriers. Therefore it is difficult to control their number in intrinsic semiconductors.

(iii) The number of electrons are equal to the number of holes in intrinsic semiconductors. Hence, we cannot have large number of only electrons or holes in intrinsic semiconductors.

**Extrinsic Semiconductor :** A semiconductor doped with suitable impurity is called extrinsic semiconductor. These are of two types :

(i) *N*-type semiconductor

(ii) *P*-type semiconductor

**Point to Remember**

Silicon is found in most of the common rocks. Sand is silicon dioxide from which silicon is extracted.

**N-type Semiconductor :** If pentavalent impurity atoms such as arsenic, antimony, phosphorus, bismuth etc. are doped to an intrinsic (pure) semiconductor, *N*-type semiconductor is obtained. Only four out of five available electrons of impurity atoms participate in forming the covalent bonds and fifth electron from each impurity atom is almost free for conduction as shown in Fig. 6.12. When a fifth group element substitutes the sites of *Si* or *Ge*, then pentavalent dopant donates one extra electron for conduction and hence is called donar impurity. Total number of conduction electrons ($n_e$) is due to the contribution of donars as well as thermally generated carriers. But the number of holes ($n_h$) are only due to thermal process. In this type of semiconductors since the majority charge carriers are negatively charged electrons, so this type of semiconductor is *N*-type semiconductor.

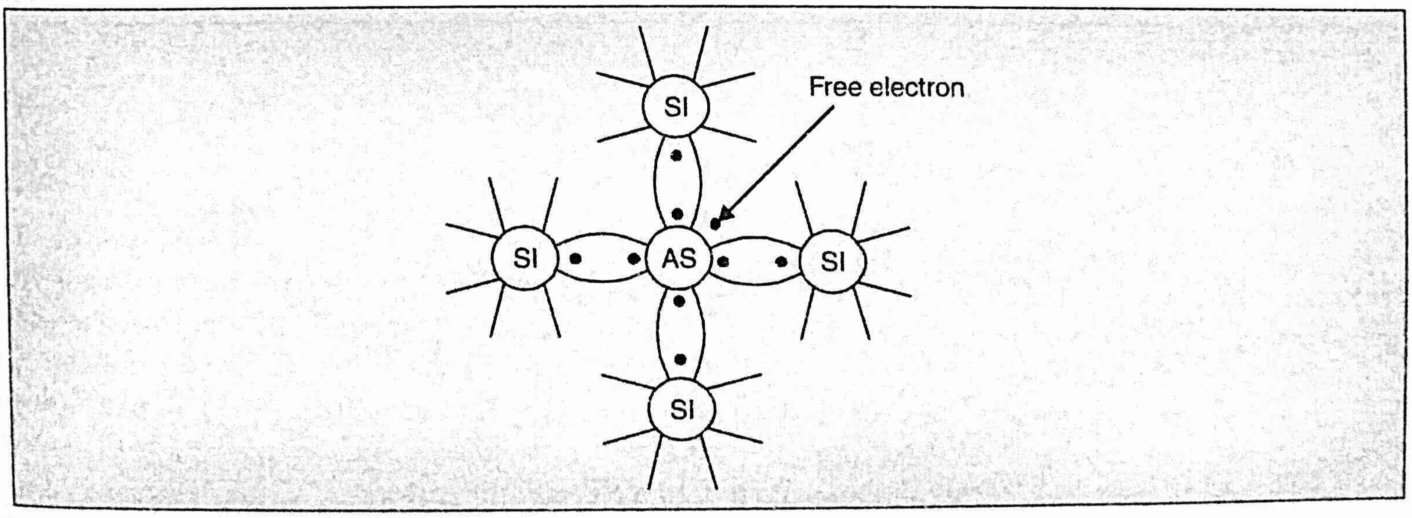


**Fig. 6.12**

There is a very little attraction between the fifth free electron and core of the impurity atom. Very small part of energy, less than 0.045 $eV$, is required to make the electron move from valence band to conduction band. The thermal energy at room temperature is enough to make the fifth electron free for the conduction. Fifth group impurity atoms are called donar atoms as they donate the electrons for conduction.

When fifth group impurity atoms are added to an intrinsic semiconductors, then energy possessed by the free electrons, due to impurity atoms, is slightly less than the energy of free electrons in the lowest energy level of the conduction band. These electrons create a lower energy level just below (0.01 $eV$ to 0.05 $eV$) the conduction band as shown in Fig. 6.13. This energy band is called donar energy level. Since the energy gap reduces due to creation of donar energy level, electrons can easily go to the conduction band, even at room temperature. Thus the conductivity of $N$-type semiconductors increases greatly.

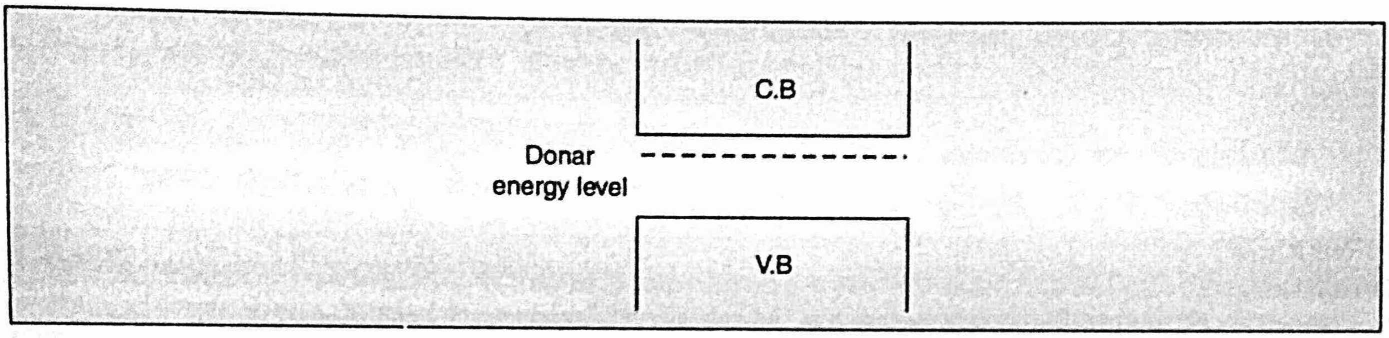


Fig. 6.13

**P-Type Semiconductor** : If trivalent atoms such as Boron, Aluminium, Gallium, indium etc. are doped to an intrinsic semiconductor, $P$-type semiconductor is obtained. Trivalent impurity atoms form only three covalent bonds with the neighbouring semiconductor atoms. One covalent bond remains incomplete due to the deficiency of electron as shown in Fig. 6.14. To fill this incomplete bond, an electron is taken from a neighbouring $Si$-$Si$ bond, which creates a vacancy or a hole there. To fill this hole, another covalent bond in the neighborhood gets broken and in this way holes are the majority current carriers and the semiconductor produced is called a $P$-type semiconductor as holes carry positive charge. These holes which move freely in a crystal lattice cause conductivity. Trivalent impurity atoms are called **acceptors** because they accept electrons from the neighbourhood bonds.

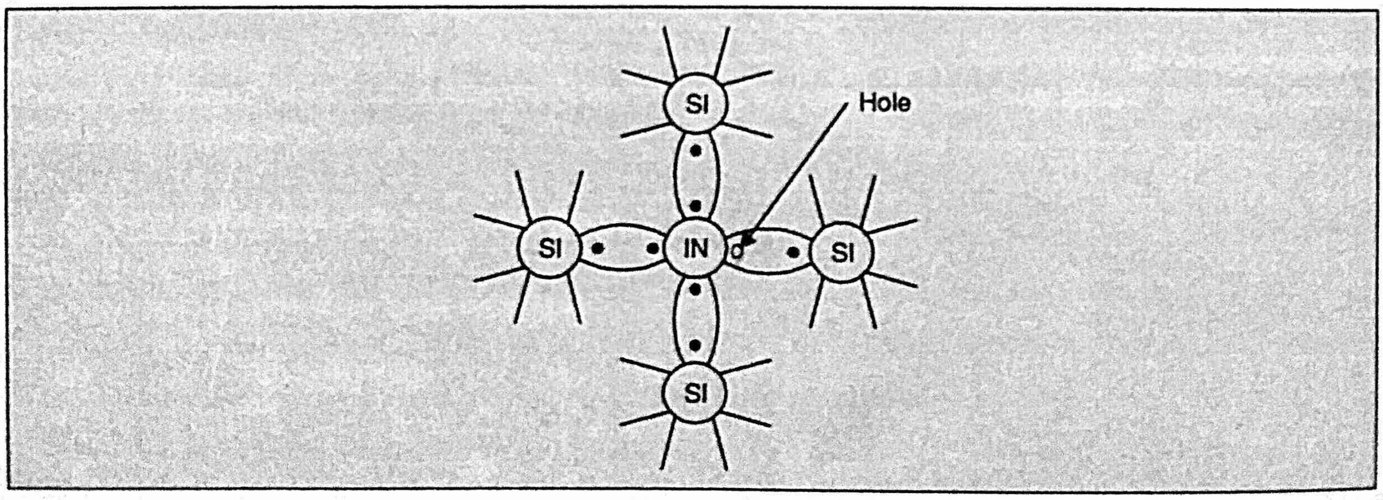


Fig. 6.14

The holes create a acceptor energy level just above the top of the valence bond. At room temperature, the electrons get sufficient thermal energy and can jump easily from the valence band to the acceptor energy level and creates further holes in the valence band as shown in Fig. 6.15.

**Density of electrons in C.B. of N-Type Semiconductor :** Let us calculate the density of electrons in conduction band and density of holes in valence band of N-type extrinsic semiconductor.

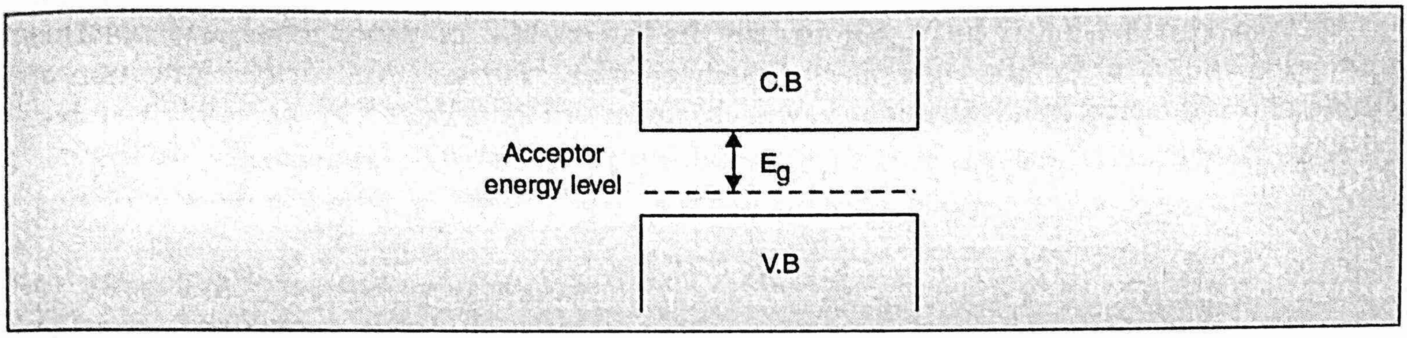


Fig. 6.15

We know that the number of electrons ($n_e$) per unit volume in conduction band is given by the relation

$$n_e = N_{eff}\, e^{\frac{E_F - E_C}{k_B T}} \qquad \ldots(i)$$

where $E_C$ is the energy corresponding to the bottom of conduction band, $N_{eff}$ is the total number of effective electrons in the band and is given by

$$N_{eff} = \frac{2LM}{\pi\hbar^2}\left(\frac{dE}{dk}\right)_{k = k_1}$$

$E_F$ is the energy corresponding to a fermi level, $k_B$ is the Boltzman's constant and $T$ is the temperature. Also, the number of vacant states per unit volume in donar level shown in Fig. 6.13 is

$$= N_d\, e^{E_d - E_F/k_B T} \qquad \ldots(ii)$$

Comparing eqns. (*i*) and (*ii*) we have,

$$N_{eff}\, e^{\frac{E_F - E_C}{k_B T}} = N_d\, e^{\frac{(E_d - E_F)}{k_B T}}$$

or

$$\frac{N_d}{N_{eff}} = e^{\frac{2E_F - E_d - E_C}{k_B T}}$$

$$\log_e\left(\frac{N_d}{N_{eff}}\right) = \frac{2E_F - E_d - E_C}{k_B T}$$

$$= \frac{2E_F}{k_B T} - \frac{(E_d + E_c)}{k_B T}$$

or
$$E_F = \frac{E_d + E_c}{2} + \frac{k_B T}{2} \log_e \left( \frac{N_d}{N_{eff}} \right) \qquad ...(iii)$$

At $T = 0K$,

$$E_F = \frac{E_d + E_c}{2}$$

At zero kelvin, Fermi level lies exactly in the middle of donar level and bottom of conduction band with the increase of temperature, Fermi level drops and at room temperature, it comes below the donar level as shown in Fig. 6.16.

Putting the value of $E_F$ from eqn. (*iii*) in eqn. (*i*), we have

$$n_e = N_{eff}\, e^{\left[\frac{E_d - E_c}{2k_B T} + \frac{1}{2}\log_e \frac{N_d}{N_{eff}}\right]} = N_{eff}\left[e^{\frac{E_d - E_c}{2k_B T}}\right]\left[\frac{N_d}{N_{eff}}\right]^{1/2}$$

$$= \sqrt{N_{eff} N_d}\left[e^{\frac{E_d - E_c}{2k_B T}}\right] = \sqrt{N_{eff} N_d}\; e^{\frac{\Delta E}{2k_B T}}$$

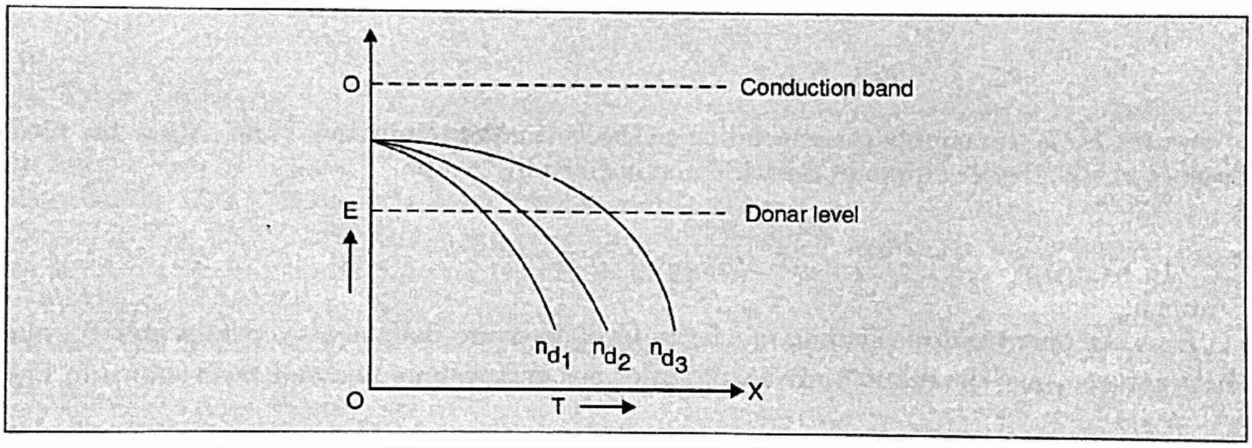


**Fig. 6.16**

where $\Delta E = E_d - E_c$ is the ionization energy of donar impurity.

Thus, we conclude that

(i) The density of electrons in the conduction band is proportional to the square root of the donar concentration.

(ii) The conductivity of intrinsic semiconductor is less than *N*-type or *P*-type semiconductor.

(iii) There is a limit on the operating temperature of semiconductor materials.

(iv) Similarly the carrier concentration of holes in the valence band of *P*-type semiconductor can be determined as

$$n_h = \sqrt{N_{eff} N_a}\; e^{\Delta E/2k_B T}$$

where $N_a$ is the number of acceptor atoms per unit volume. Here, the Fermi level lies exactly midway between top of valence band and acceptor level (Fig. 6.15). With increase in temperature, it shifts upwards.

## 5.8 SEMICONDUCTORS

It has been observed that certain substances like germanium, silicon, etc. have resistivity ($10^{-4}$ to 0.5 ohm-metre) between good conductors (like copper) have resistivity $1.7 \times 10^{-8}$ ohm-metre and insulators like glass having resistivity $9 \times 10^{11}$ ohm-metre. These substances are known as semiconductors. ***A substance which has resistivity between conductor and insulator is known as semiconductor.***

A semiconductor may also be defined ***as an element with electrical properties between those of conductors and insulators.***

Semiconductors may be classified as under :

- Semiconductors
  - Intrinsic or Pure semiconductors
  - Extrinsic or Impure semiconductors
    - P-type
    - N-type

### 1. Intrinsic Semiconductors

***A semiconductor in an extremely pure form is known as intrinsic semiconductor.***

### 2. Extrinsic Semiconductors

The electrical conductivity of intrinsic semiconductor can be increased by adding some impurity in it. Such semiconductors are known as impurity or extrinsic semiconductors.

### 5.8-1 INTRINSIC SEMICONDUCTOR MATERIALS

The two most frequently used semiconductor materials are germanium (Ge) and silicon (Si).

### 1. Germanium (Ge)

Consider the case of pure germanium semiconductor. It has thirty two electrons as shown in fig. (12). Two electrons are in the first orbit, eight electrons are in second orbit, eighteen electrons in third orbit and four electrons in the outer or valence orbit. So out of thirty two electrons, twenty eight are tightly bound to the nucleus while the remaining four revolve in the outer-most orbit. These four electrons are known as ***valence electrons.*** Nucleus with twenty eight tightly bound electrons form the ***'positive core'*** of the atom.

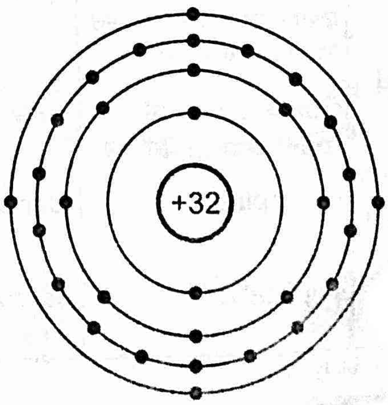


**Fig. 12. Germanium structure.**

Fig. (13) shows how various germanium atoms are held through covalent bonds.

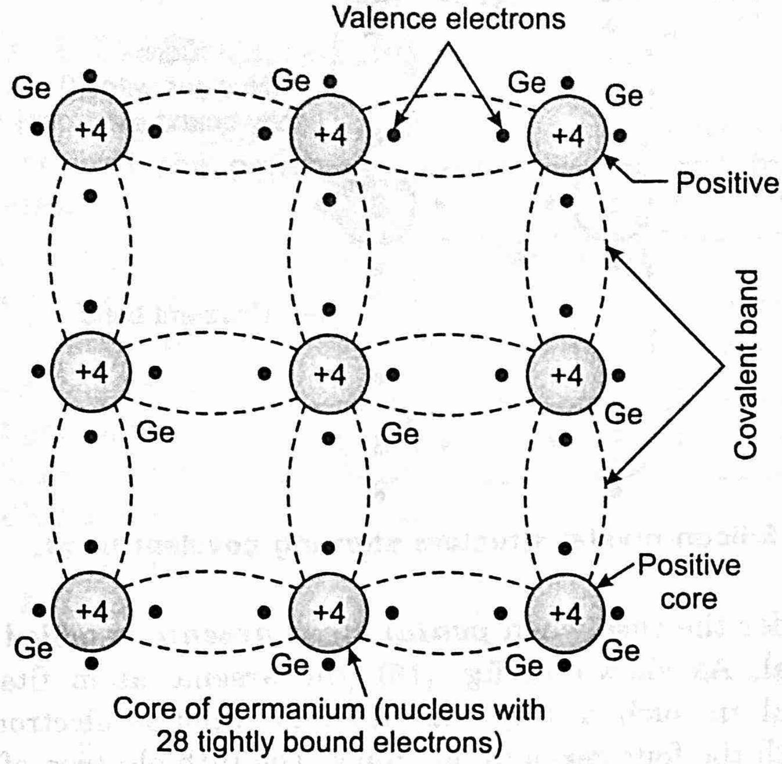


**Fig. 13. Germanium crystal structure showing covalent bond.**

## 2. Silicon (Si)

The atomic number of silicon is 14. An isolated silicon atom has 14 protons and 14 electrons. There are two electrons in first orbit, eight electrons in second orbit and four electrons in third orbit. Therefore, the four electrons are in valence orbit as shown in fig. (14). The ***core*** has a net charge + 4 because it contains 14 protons in nucleus and 10 electrons in first and second orbits.

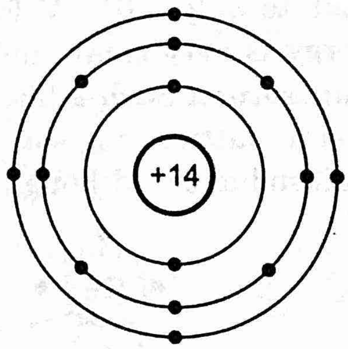


**Fig. 14. Silicon structure.**

Fig. (15) shows how various silicon atoms are held through covalent bonds.

It is important to mention that conductors have one valence electron, semiconductor have four valence electrons and insulators have eight valence electrons. The valence electron/electrons is/are the key of conductivity.

## 5.9 N-TYPE EXTRINSIC SEMICONDUCTOR

***When a small amount of pentavalent impurity (like Arsenic) is added to a pure semiconductor crystal, the resulting crystal is called as N-type extrinsic semiconductor.***

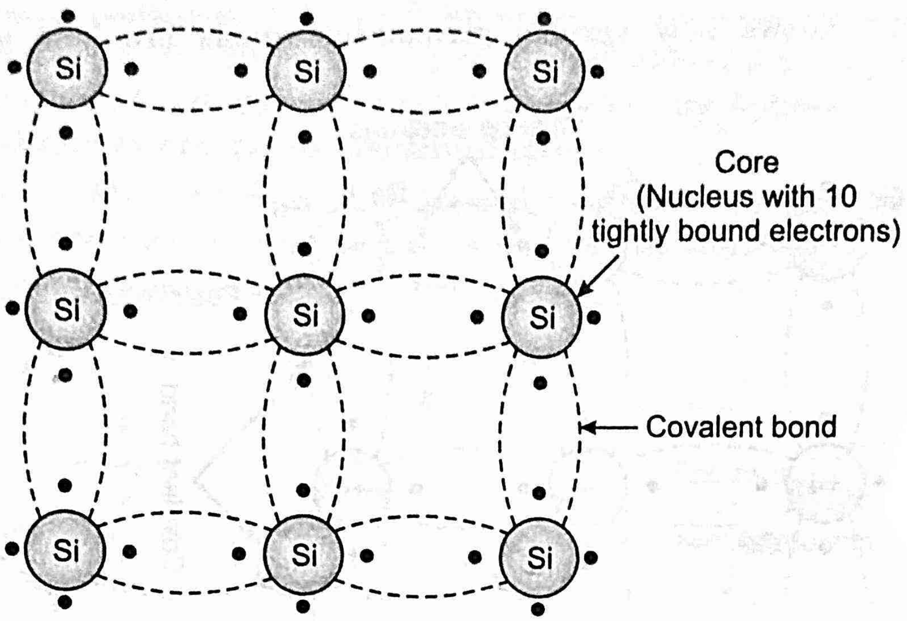


**Fig. 15. Silicon crystal structure showing covalent bond.**

Let us consider the case when ***pentavalent arsenic*** is added to pure germanium crystal. As shown in fig. (16), the arsenic atom fits in the germanium crystal in such a way that its four valence electrons from covalent bonds with the four germanium atoms. The fifth electron of arsenic atom is not covalently bonded but it is loosely bound to the parent arsenic atom. This electron is available as a carrier of current. The amount of energy needed to detach this fifth valence electron from impurity atom is of the order to only 0.01 eV for Ge and 0.05 eV for Si using As impurity. This energy is very small and may be provided with thermal agitation at room temperature. Such a liberated ***valence electron*** is then free to move in the crystal lattice in the same way as free electrons in an intrinsic semiconductor. Although each arsenic atom provides only one free electron,

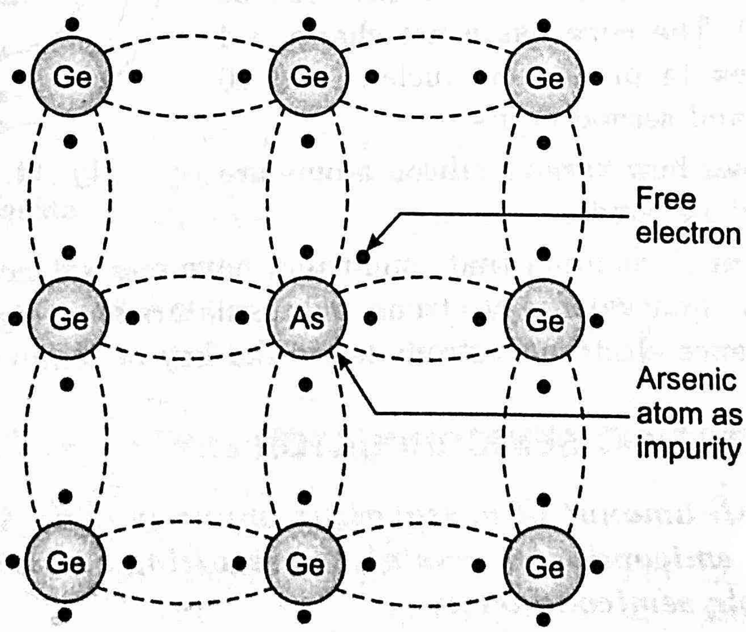


**Fig. 16. Crystal lattice with one germanium atom displaced by arsenic atom.**

yet an extremely amount of arsenic impurity provides enough atoms to supply millions of free electrons.

## 5.10 P-TYPE EXTRINSIC SEMICONDUCTOR

***When a small amount of trivalent impurity (like Boron) is added to a pure crystal the resulting crystal is called a P-type extrinsic semiconductor.***

Let us consider the case when ***trivalent boron*** is added to pure germanium crystal. As shown in fig. (17), each atom of boron fits into the germanium crystal with only three covalent bonds. This is because the three valence electrons of boron atom form covalent bonds with the valence electrons of germanium atom. In the fourth covalent bond, only germanium atom contributes one valence electron and there is deficiency of one electron which is called a ***hole***. In other words we can say that the fourth bond is incomplete; being short of one electron. Therefore, for each boron atom added, one ***hole*** is created. A small amount of boron provides millions of holes.

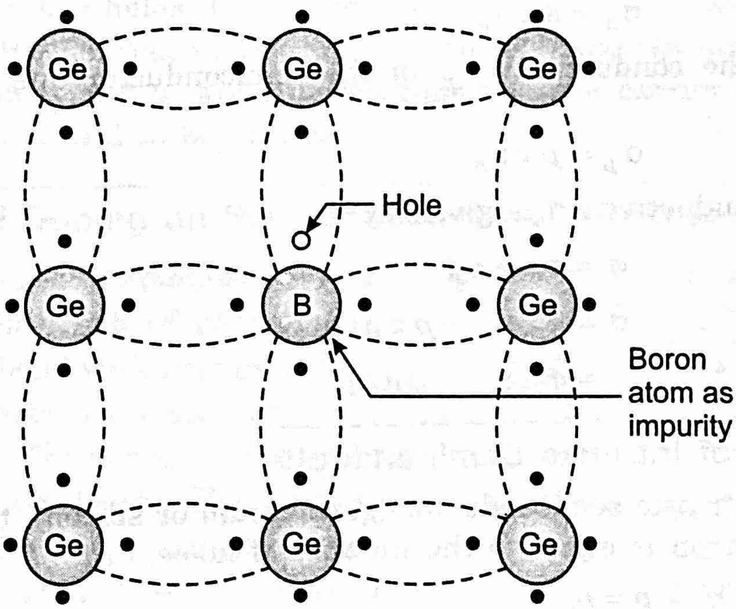


**Fig. 17. Crystal lattice with one germanium atom displaced by trivalent impurity atom (boron).**